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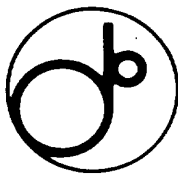
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V.A. Polyakov, M. Poulet, Yu.D. Prokoshkin, S.A. Sadovsky,  
V.D. Samoylenko, P.M. Shagin, H. Shimizu, A.V. Shtannikov,  
A.V. Singovsky, J.P. Stroot, V.P. Sugonyaev, K. Takamatsu,  
M.R. Torquati, T. Tsuru, and Y. Yasu

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# Study of the $\pi^0\pi^0$ system in $pp$ central collisions at 450 GeV/c

D. Alde<sup>a</sup>, R. Bellazzini<sup>b</sup>, F.G. Binon<sup>c</sup>, M. Boutemour<sup>d</sup>, A. Brez<sup>b</sup>, C. Bricman<sup>e</sup>,  
S.V. Donskov<sup>f</sup>, M. Gouanère<sup>e</sup>, S. Inaba<sup>g</sup>, A.V. Inyakin<sup>f</sup>, T. Ishida<sup>g</sup>, H. Kawai<sup>h</sup>,  
G.V. Khaustov<sup>f</sup>, T. Kinashi<sup>i</sup>, M. Kobayashi<sup>g</sup>, E.A. Knapp<sup>a</sup>, A.A. Kondashov<sup>f</sup>,  
A.V. Kulik<sup>f</sup>, G.L. Landsberg<sup>f</sup>, A.A. Lednev<sup>f</sup>, V.A. Lishin<sup>f</sup>, M.M. Massai<sup>b</sup>,  
T. Nakagawa<sup>j</sup>, T. Nakamura<sup>k</sup>, J.P. Peigneux<sup>e</sup>, S.A. Polovnikov<sup>f</sup>, V.A. Polyakov<sup>f</sup>,  
M. Poulet<sup>e</sup>, Yu.D. Prokoshkin<sup>f</sup>, S.A. Sadovsky<sup>f</sup>, V.D. Samoylenko<sup>f</sup>, P.M. Shagin<sup>f</sup>,  
H. Shimizu<sup>l</sup>, A.V. Shtannikov<sup>f</sup>, A.V. Singovsky<sup>f</sup>, J.P. Stroot<sup>m</sup>, V.P. Sugonyaev<sup>f</sup>,  
K. Takamatsu<sup>k</sup>, M.R. Torquati<sup>b</sup>, T. Tsuru<sup>g</sup>, and Y. Yasu<sup>g</sup>

**GAMS collaboration**

- (a) *Los Alamos National Laboratory, Los Alamos, NM 27544, USA*
- (b) *University of Pisa and INFN, Pisa, Italy*
- (c) *Université Libre de Bruxelles, CP 229, B-1050 Brussels, Belgium*
- (d) *Laboratory for Particle Physics – CERN, CH-211, Geneva 23, Switzerland*
- (e) *Laboratoire d'Annecy de Physique des Particules, F-74019 Annecy-le-Vieux, France*
- (f) *Institute for High Energy Physics, Protvino, 142284 Russia*
- (g) *National Laboratory for High Energy Physics – KEK, Tsukuba, Ibaraki 305, Japan*
- (h) *Chiba University, Inage-ku, Chiba 263, Japan*
- (i) *Research Center for Nuclear Physics, Osaka, Japan*
- (j) *Tohoku University, Aoba-ku, Sendai 980, Japan*
- (k) *Miyazaki University, Miyazaki 889-21, Japan*
- (l) *Yamagata University, Yamagata 990, Japan*
- (m) *Institut Interuniversitaire des Sciences Nucléaires, Brussels, Belgium*

## Abstract

The effective mass spectrum of  $\pi^0$  pairs produced in  $pp$  central collisions ( $pp \rightarrow p_f \pi^0 \pi^0 p_s$ ) at 450 GeV/c,  $\sqrt{s} = 29$  GeV, below 1 GeV differs from that observed in peripheral charge exchange reactions. In particular, there is a large number of events between  $\pi\pi$ -threshold and 1 GeV, that interfere with  $f_0(980)$  destructively. The possible existence of a broad S-wave state is suggested.

Dedicated to the memory of our colleague Prof. Teruo Nakamura

# Introduction

The present study investigates  $\pi^0\pi^0$  final states produced in the central collision reaction

$$pp \rightarrow p_f X^0 p_s, \quad X^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma \quad (1)$$

with a 450 GeV/c momentum incident proton beam at CERN SPS.

The study of scalar mesons is important for meson spectroscopy [1]. The assignment of the ground state scalar  $q\bar{q}$  nonet is not straightforward and many  $IJ^{PC} = 00^{++}$  resonances are reported in various experiments. Some might finally be identical objects, but some, at least, might be non- $q\bar{q}$  mesons – *i.e.* exotics.

In GAMS experiments, two different types of reactions have been investigated so far by using similar detector setups: the charge-exchange reaction (CEX)

$$\pi^- p \rightarrow X^0 n, \quad X^0 \rightarrow n\gamma \quad (2)$$

and the central collision reaction (1). It is expected that in the latter process at large CM energy the Double Pomeron Exchange (DPE) [2] contribution would be large, so that it is considered to be a gluon-rich process. The comparison of these two types of different production reactions may bring clues to search for glueballs and hybrids.

Observation of neutral  $\pi^0\pi^0$  pairs has the advantage to be free from  $\rho^0$  decays which dominate the charged  $\pi^+\pi^-$  mode. We present the observation of low mass  $2\pi^0$  events produced in central collisions, a region where the spectrum appears to be significantly different from that produced in CEX. These events apparently interfere with  $f_0(980)$ , suggesting a possible broad S-wave state. The comparison of  $f_0(980)$  production in both reactions (1) and (2) [3] is also discussed.

## 1. Detector setup

The exclusive measurement of reaction

$$pp \rightarrow p_f X^0 p_s, \quad X^0 \rightarrow n\gamma \quad (3)$$

was performed with the NA12/2 setup that was located in the SPS North Area as shown in Fig. 1. Energy and position of the gammas which are produced by the decay of  $X^0$  are measured with the electromagnetic hodoscope calorimeter GAMS-4000 [5]. The forward proton momentum is measured by a magnetic spectrometer with microstrip gas chambers [6], and the recoil proton momentum is measured by a Recoil Proton Detector (RPD) [7]. The detailed description of the trigger conditions is given elsewhere [8].

## 2. Event selection and acceptance correction

80 million events with a fast track in the forward spectrometer, a track in the RPD and  $n$  gammas ( $n \geq 2$ ) after event reconstruction, have been collected. Out of these, 130 thousand four-gamma events corresponding to the reaction  $pp \rightarrow p 4\gamma p$  have been selected by requiring that no signal appears in the sandwich aperture veto counters and that each

$\gamma$  would have an energy above a threshold of 2 GeV. The two-dimensional plot of the invariant mass of any two gammas versus that of the two others is shown in Fig. 2, taking all possible combinations into account. There is a clear peak of  $\pi^0\pi^0$  events.

$\pi^0$ s are selected by requiring  $120 < M_{2\gamma} < 160$  MeV. Events that may be identified as  $\pi^0\pi^0$  after 3C fit were accepted if  $\chi^2/n_{d.o.f} < 1.5$  ( $n_{d.o.f} = 12$ ). The resolution of  $\pi^0\pi^0$  mass after the fit is about 10 MeV in our relevant mass region.

Finally,  $8.5 \cdot 10^4$  events remained as the sample of reaction (1)  $\pi^0\pi^0$  events.

The acceptance correction was calculated by Monte Carlo simulation taking the geometry of the setup and event selection criteria into account. Major sources which affect the acceptance are: (i) the  $E_\gamma < 2$  GeV cut, (ii) the geometrical acceptance of the setup, in particular that from the hole in the central part of the GAMS-4000<sup>1</sup>, and (iii) the minimum distance between two overlapping  $\gamma$  clusters.

The simulation has also been performed with an effective hole size increased by 5 mm ( $\approx 2\sigma$  position resolution), and with a  $E_\gamma$  threshold fluctuation of 100 MeV (*i.e.* the energy resolution at  $E_\gamma = 2$  GeV). The comparison of both simulations shows no significant structural difference in the spectra. The fluctuation of acceptance corrected event numbers is less than 5% in total. It may be regarded as an estimate of the systematic error.

### 3. Observed mass spectrum

The observed mass spectrum of the  $\pi^0\pi^0$  system for the accessible  $|t|$  region after acceptance correction is shown in Fig. 3. A large number of events is observed between 300 MeV and 1 GeV. A “shoulder” appears around 900 MeV. These features are similar to those of the  $\pi^+\pi^-$  system [9-11] (apart from the  $\rho^0$  contribution) and of the  $\pi^0\pi^0$  system [11] observed in  $pp$  central production experiments so far. The shoulder-like structure appears in a region below that of the mass value of  $f_0(980)$  recorded in the PDG tables [4].

### 4. Feynmann $x_F$ and $t$ distributions

The Feynman  $x_F$  distributions of  $\pi^0\pi^0$  system, of fast and of slow protons are shown in Fig. 4(a). The  $x_F$  of the  $\pi^0\pi^0$  system are concentrated between 0 and 0.3. This reflects a limited acceptance of the setup which vanishes at negative  $x_F$ .

Fig. 4(b) shows the exponential  $t$ -distributions of the whole data set, where  $t_1$  is the momentum transfer of the fast proton and  $t_2$  is that of the slow proton. The slope parameter of single Pomeron exchange  $pp$  diffractive scattering is  $b \sim (7.9 + 0.7 \ln P_{lab.}) (\text{GeV}/c)^{-2}$  [12]. The DPE  $t$ -distribution is proportional to  $\exp [b(t_1 + t_2)/2]$  [13], where  $b/2 = 6 (\text{GeV}/c)^{-2}$  for  $P_{lab.} = 450 \text{ GeV}/c$ . The best fit values of the slope parameter for the present  $\pi^0\pi^0$  set of data (Fig. 4(b)),  $5.93 \pm 0.09 (\text{GeV}/c)^{-2}$  for  $t_1$  and  $6.12 \pm 0.07 (\text{GeV}/c)^{-2}$  for  $t_2$ , are in a similar range.

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<sup>1</sup>The GAMS-4000 detector, which consists of  $64 \times 64$  lead-glass cells, has a hole of  $2 \times 2$  cells in its center for the passage of the beam and of the forward fast protons.

## 5. Analysis of the mass spectrum

In the  $\pi^0\pi^0$  mass spectrum (Fig. 3), the “shoulder-like” structure in the region below the  $f_0(980)$  mass seems to arise from the interference of this state with the lower-mass events. Here we will give two different kinds of fits with introduction of an appropriate kinematical factor. If the observed spectrum is due to the DPE it may be expressed as a function of the Pomeron-Pomeron cross section  $\sigma_{PP}$  [13]:

$$\frac{d^2\sigma_{DP}}{dm^2} \sim \left(\frac{\beta^4}{b^2}\right) \left(\frac{1}{m^2}\right) \sigma_{PP}(m), \quad (4)$$

where  $\beta$  is a pp-Pomeron coupling.  $\sigma_{PP}$  may be described by invariant amplitude as

$$\sigma_{PP} = \frac{|\mathbf{p}|^{\pi\pi}}{4\pi\sqrt{s}} |\mathcal{M}|^2. \quad (5)$$

The Adler zero condition is introduced on the invariant amplitude  $\mathcal{M}$ , as

$$\mathcal{M} \rightarrow \frac{s - m_\pi^2}{s} \mathcal{M}. \quad (6)$$

Firstly we conventionally introduce the following invariant amplitude<sup>2</sup>:

$$\begin{aligned} \mathcal{M} &= \mathcal{M}_0 + \mathcal{M}_{exp} \\ &= \frac{\xi_{f_0}}{(s - m_{f_0}^2) + im_{f_0}\Gamma_{f_0}^{tot}(s)} + a \cdot e^{i\theta} (\sqrt{s}/m_\pi - b)^c \cdot \exp(-d\sqrt{s}/m_\pi). \end{aligned} \quad (7)$$

The first term  $\mathcal{M}_0$  is a Breit-Wigner form representing  $f_0(980)$ , where  $\xi_{f_0}$  is the product of couplings of  $f_0$  to the initial and to the final states.  $m_{f_0}$  is the  $f_0$  mass. The second term  $\mathcal{M}_{exp}$  with four free parameters  $a$ ,  $b$ ,  $c$  and  $d$ , is a phenomenological formula that reproduces the characteristic distribution of the lower-mass  $\pi^0\pi^0$  events.  $\theta$  in  $\mathcal{M}_{exp}$  is the relative phase between amplitudes for  $f_0$  and the lower-mass contribution.  $\Gamma^{tot}(s)$  in Eq. (7) is the sum of partial widths of  $\pi\pi$  and  $K\bar{K}$  channels, represented by coupling constants  $g_{\pi\pi}$  and  $g_{K\bar{K}}$ :

$$\begin{aligned} \Gamma_{f_0}^{tot}(s) &= \Gamma_{f_0}^{\pi\pi}(s) + \Gamma_{f_0}^{K\bar{K}}(s) = \frac{|\mathbf{p}|^{\pi\pi}}{8\pi m_{f_0}^2} g_{f_0\pi\pi}^2 + \frac{|\mathbf{p}|^{K\bar{K}}}{8\pi m_{f_0}^2} g_{f_0K\bar{K}}^2 \\ |\mathbf{p}|^{\pi\pi} &= \sqrt{s/4 - m_\pi^2}, \quad |\mathbf{p}|^{K\bar{K}} = \sqrt{s/4 - m_K^2}, \end{aligned}$$

where we take  $g_{K\bar{K}}/g_{\pi\pi} = 1.5$  for  $f_0(980)$  [24] and 1 for  $f_2(1270)$ .

The dashed curve of Fig. 5(a) shows the result of the fit of the efficiency corrected mass spectrum with Eq. (7) ( $\chi^2/n_{d.o.f.} = 38/27$ ), including another Breit-Wigner function to take care of a possible  $f_2(1270)$  contribution. The values of mass and width of the resonant states are:

$$\begin{aligned} m_{f_0} &= 962 \pm 10 \text{ MeV}, \quad \Gamma_{f_0\pi\pi} = 77 \pm 15 \text{ MeV}, \\ m_{f_2} &= 1265 \pm 10 \text{ MeV}, \quad \Gamma_{f_2\pi\pi} = 205 \pm 20 \text{ MeV}. \end{aligned}$$

<sup>2</sup>Ref. [11] explains the spectrum by the interference between  $f_0(980)$  and an “S-wave background”. Eq. (7) is essentially identical to that used in [11].

The data have also been fitted with a second Breit-Wigner amplitude  $\mathcal{M}_c$  that replaces  $\mathcal{M}_{exp}$  in (7) [14]:

$$\begin{aligned}\mathcal{M} &= \mathcal{M}_0 + \mathcal{M}_c \\ &= \frac{\xi_{f_0}}{(s - m_{f_0}^2) + im_{f_0}\Gamma_{f_0}^{tot}(s)} + \frac{\xi_c e^{i\theta}}{(s - m_c^2) + im_c\Gamma_c^{tot}(s)},\end{aligned}\quad (8)$$

testing the hypothesis of a low mass S-wave resonance.  $\xi$ s represent the respective coupling strengths to the initial and final channels,  $m_c$  is the mass value of the lower-mass S-wave state, and  $\theta$  is the relative phase between production amplitudes of  $f_0$  and this S-state.<sup>3</sup> The result of the fit is shown in Fig. 5(b) ( $\chi^2/n_{d.o.f.} = 56/28$ ) with masses and widths of:

$$\begin{aligned}m_{f_0} &= 955 \pm 10 \text{ MeV}, & \Gamma_{f_0\pi\pi} &= 69 \pm 15 \text{ MeV}, \\ m_{f_2} &= 1260 \pm 10 \text{ MeV}, & \Gamma_{f_2\pi\pi} &= 187 \pm 20 \text{ MeV} \\ m_c &= 780 \pm 30 \text{ MeV}, & \Gamma_{c\pi\pi} &= 780 \pm 60 \text{ MeV}.\end{aligned}$$

The relative phase,  $\theta$ , is  $277^\circ \pm 10^\circ$ . Here note that values of mass and width of a broad Breit-Wigner are strongly dependent both on the choice of the kinematical factor and on its parametrization. The large values of  $m_c$  and of  $\Gamma_{c\pi\pi}$  are mainly due to the DPE kinematical factor. Also, if we use  $i\sqrt{s}\Gamma(s)$  instead of  $im\Gamma(s)$  in Eq. (8), we obtain a best fit value of  $m_c = 580$  MeV. Thus there is a rather large uncertainty on the S-wave state mass that might lie between 500 and 800 MeV and width of several hundred MeV.

Both of these fits reproduce the “destructive” interference of  $f_0(980)$  with other S-wave events with similar  $\chi^2$ . Mass values of both  $f_0$  and  $f_2$  are somewhat lower than PDG mean values [4] and differ in both fits from each other. Quoted errors include a systematic uncertainty that does not affect the comparison of the two hypotheses.

The  $f_0(980)$  to  $f_2(1270)$  production ratio over the entire  $t$  range is  $1/(7.6 \pm 4.0)$ , which is large compared to that in CEX [3, 15];  $75 \pm 10 \text{ nb} / 2.6 \pm 0.3 \mu\text{b} \sim 1/(35 \pm 6)$ .

## Discussion

In the past decade, much effort has been put on the analysis and understanding of the  $\pi\pi$ -scattering phase shift [16-20]. The 1994 PDG tables [4] contained only two isoscalar scalar resonances below 1300 MeV: the narrow  $f_0(980)$  and the very broad  $f_0(1300)$ .

On the other hand, the  $pp$  central collision experiments have reported the existence of a large S-wave contribution in the low-mass region of  $\pi\pi$  system [9-11], as it is also found in this work. This has been treated so far by two different procedures: either (a) by a large  $s$ -dependence of the production amplitude [16], or (b) by an exponential-type function, like  $\mathcal{M}_{exp}$  in Eq. (7) [11]. However, in (a) there remains the question of the physical origin of the  $s$ -dependence of the production amplitude, and in (b) the physical character of the S-wave contribution is obscure.

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<sup>3</sup>The interaction between the two final pions gives an extra factor  $\exp(i\delta_{\pi\pi})$  to  $\mathcal{M}$ ,  $\delta_{\pi\pi}$  being the scattering phase shift, which is irrelevant to the mass spectra.



The present analysis shows that the lower-mass events can also be fitted with a simple Breit-Wigner<sup>4</sup>. It might then be identified as the controversial  $\sigma$ -state that has been reinstated in the 1996 issue of the PDG [21] after its removal in 1976, and whose need has been revived in recent theoretical studies [18, 22-24].

In summary, the analysis of  $\pi^0\pi^0$  system produced in the  $pp$  central collisions confirms a large concentration of S-wave events below 1 GeV, which interferes with  $f_0(980)$  destructively. This would be compatible with the existence of a broad S-wave state below 1 GeV, but its coherence with the known  $\pi\pi$ -scattering phase shifts is still the object of controversy that bears on basic non-perturbative QCD concepts [23-25]. The production ratio of  $f_0(980)$  to  $f_2(1270)$  in the present observation is significantly larger than that in the charge exchange reaction.

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<sup>4</sup>Note that simple phase space cannot interfere with  $f_0(980)$ .

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## Figure captions

Fig. 1. Experimental setup NA12/2. GAMS-4000: hodoscope electromagnetic calorimeter made of lead-glass cells; HC-240: modular hadron calorimeter;  $S_{1-3}$ : scintillation counters;  $H_{1,2}$ : beam hodoscopes;  $LH_2$ : liquid hydrogen target; RPD: recoil proton detector;  $AH_{1,2}$ : scintillation counters;  $SW_{1,2}$ : aperture defining sandwich counters;  $MWPC_{1-4}$ : multiwire proportional chambers;  $MSGC_{1-4}$ : microstrip gas chambers; HC-9 and GAMS-64: hadron and photon hodoscope calorimeters.

Fig. 2. Digamma mass versus digamma mass distribution in  $4\gamma$  events.

Fig. 3. Mass spectrum of  $\pi^0\pi^0$  system within entire t-region (corrected for acceptance).

Fig. 4(a). Feynmann  $x_F$  distributions of slow proton (left),  $\pi^0\pi^0$  system (center) and fast proton (right) (before efficiency correction). (b). t-distribution of each proton vertex (after efficiency correction).

Fig. 5.(a)  $\pi^0\pi^0$  mass spectrum (corrected for detection efficiency). The dashed line represents the fit by exponential-type function (7). (b). Same as in (a), but fitted with two Breit-Wigners (8).

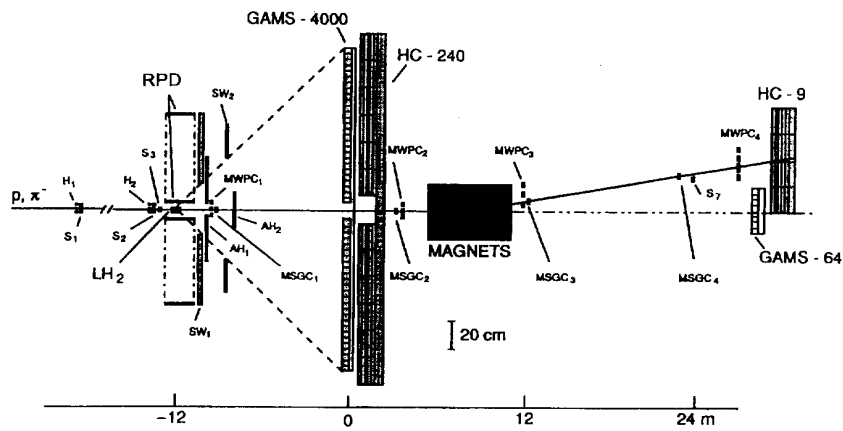


Figure 1:

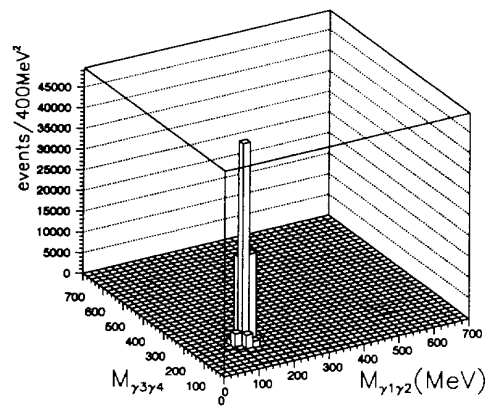


Figure 2:

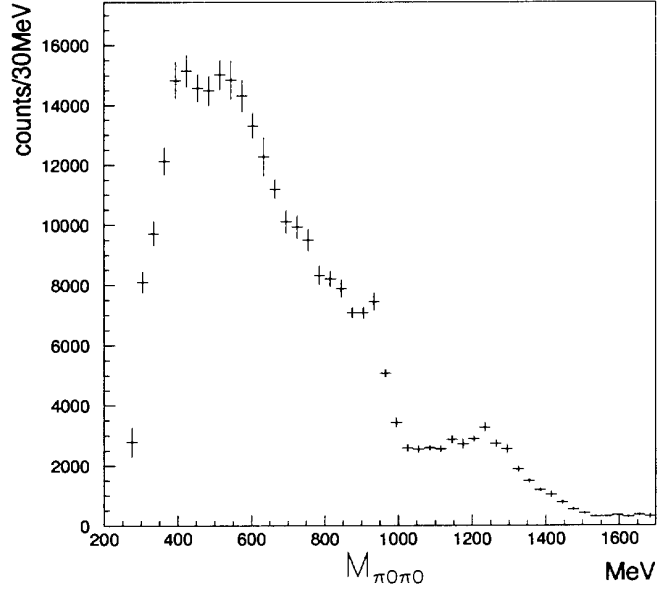


Figure 3:

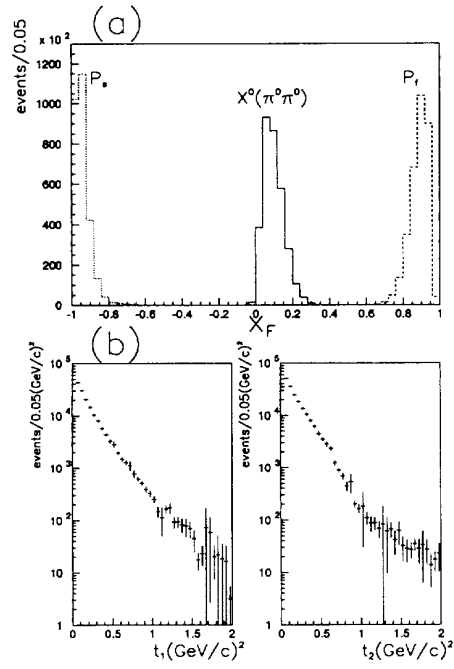


Figure 4:

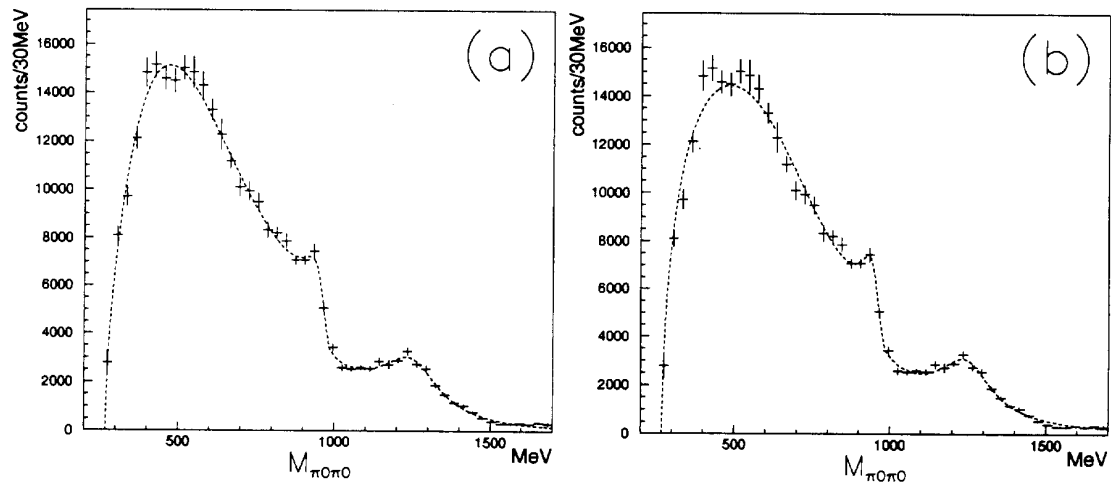


Figure 5:

